

ULTRA-FINE-SCALE FILAMENTARY STRUCTURES IN THE OUTER CORONA AND THE SOLAR MAGNETIC FIELD

RICHARD WOO

Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, MS 238-725, Pasadena, CA 91109; richard.woo@jpl.nasa.gov

Received 2005 November 1; accepted 2006 February 1; published 2006 February 21

ABSTRACT

Filamentary structures following magnetic field lines pervade the Sun's atmosphere and offer us insight into the solar magnetic field. Radio propagation measurements have shown that the smallest filamentary structures in the solar corona are more than 2 orders of magnitude finer than those seen in solar imaging. Here we use radio Doppler measurements to characterize their transverse density gradient and determine their finest scale in the outer corona at 20–30 R_{\odot} where open magnetic fields prevail. Filamentary structures overlying active regions have the steepest gradient and finest scale, while those overlying coronal holes have the shallowest gradient and least finest scale. Their organization by the underlying corona implies that these subresolution structures extend radially from the entire Sun, confirming that they trace the coronal magnetic field responsible for the radial expansion of the solar wind. That they are rooted all over the Sun elucidates the association between the magnetic field of the photosphere and that of the corona, as revealed by the similarity between the power spectra of the photospheric field and the coronal density fluctuations. This association along with the persistence of filamentary structures far from the Sun demonstrate that subresolution magnetic fields must play an important role not only in magnetic coupling of the photosphere and corona, but also in coronal heating and solar wind acceleration through the process of small-scale magnetic reconnection. They also explain why current widely used theoretical models that extrapolate photospheric magnetic fields into the corona do not predict the correct source of the solar wind.

Subject heading: Sun: corona

1. INTRODUCTION

One of the most striking features of images of the Sun is the extent to which the corona is permeated by filamentary structures (see, e.g., Lockyer 1874; Menzel 1959; Golub & Pasachoff 1997; Scharmer et al. 2002; Aschwanden 2004), whose existence has attracted attention for a long time (Alfvén 1963; Parker 1964; Litwin & Rosner 1993; Isobe et al. 2005). Radio propagation measurements show that the outer corona is also highly filamentary, with a continuum of spatial scales that extends down to 1 km or 1.4×10^{-3} arcsec at the Sun, more than 2 orders of magnitude finer than the observational limit of current solar imaging (Woo 1996a). We term these subresolution structures ultra-fine-scale filamentary structures.

Contrary to the impression that highly nonradial magnetic fields shape the density structure of solar eclipse pictures (Munro & Jackson 1977; Hundhausen 1977), the synthesis of coronal and solar measurements has shown that the coronal magnetic field is predominantly radial (Woo 2005 and references therein), as suggested by earlier polarization measurements of magnetic field direction (Eddy et al. 1973; Arnaud & Newkirk 1987; Habbal et al. 2001). While coronal and solar wind observations have been converging on a unified picture of the magnetic field in the corona, progress has also been made in observing and understanding small-scale magnetic fields of the photosphere (Schrijver et al. 1997, 1998; Cattaneo 1999; Abramenko et al. 2001; Sánchez Almeida 2003; Domínguez Cerdeña et al. 2003; Trujillo Bueno et al. 2004).

In this Letter, we further characterize the ultra-fine-scale filamentary structures in the outer corona using radio propagation measurements. The results reveal that the heretofore hidden coronal filamentary structures unify the aforementioned observations by providing the key missing observational link between the photospheric and coronal fields, and demonstrating how sub-resolution and/or small-scale magnetic fields must play an important role in coronal heating and solar wind acceleration.

2. RADIO OBSERVATIONS AND RESULTS

Observations of a wide range of radio propagation and scattering phenomena have been used to probe the solar corona for five decades (see, e.g., Ekers & Little 1971; Hewish 1972; Bird & Edenhofer 1990; Woo 1992, 1996b; Grall et al. 1996). Ranging and Doppler measurements made with coherent spacecraft radio signals became available with the advent of space exploration. Used for navigation purposes, ranging measures distance, and Doppler observes the velocity of the spacecraft. In terms of the corona, ranging probes the path-integrated electron density, while Doppler measures its time variation with high sensitivity and high temporal resolution (e.g., Bird & Edenhofer 1990).

Figure 1a, which is adapted from Pätzold et al. (1996), shows the trajectory of the *Ulysses* spacecraft as seen from Earth during the observing period of 1995 February 23–March 15 (days of year 54–74). The spacecraft radio path traverses and probes the corona from pole to equator at a distance of 20–30 R_{\odot} , a distance high above the closed structures of the inner corona where only open field lines presumably prevail. Included in Figure 1a is the corresponding variation in total electron content (path-integrated electron density) observed directly by radio ranging and plotted every 30 minutes. This time series is replotted in Figure 1b along with the polarized brightness (pB) of the Mauna Loa Mk III K-coronameter at 1.15 R_{\odot} and hence the path-integrated density at the base of the corona.

The similarity between the inner and outer coronal density profiles of Figure 1b, originally shown and discussed by Woo & Habbal (1999), is the first of a variety of observations that has shown that plasma signatures at the base of the corona (imprint of the Sun) appear radially extended in interplanetary space. The radial extension of density into interplanetary space can only imply that both the coronal magnetic field and the solar wind flow are predominantly radial and that the solar wind originates from the entire Sun rather than flowing exclusively from coronal holes (Woo et al. 2000 and references therein).

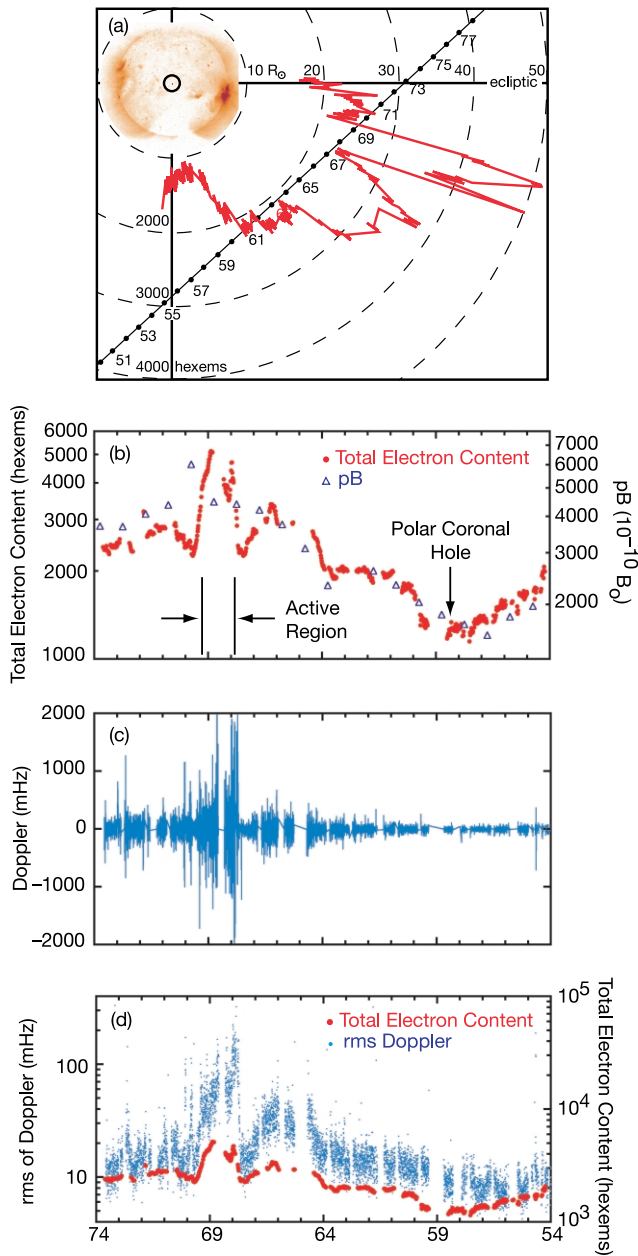


FIG. 1.—Panel *a* (adapted from Fig. 1 of Pätzold et al. 1996) shows the Sun as viewed from Earth and the trajectory of *Ulysses* as its radio path probes the solar corona from pole to equator. The dots represent the location of the radio path in the plane of the sky for each day of year (DOY) in 1995. Also included are measurements of total electron content (path-integrated electron density) inferred from ranging measurements sampled at a rate of 1 per 30 minutes. The *Yohkoh* soft X-ray picture of the Sun corresponds to DOY 68 to show that at the time of maximum observed electron density, the *Ulysses* radio path was probing the corona radially above the active region. Panel *b* is adapted from Fig. 1b in Woo & Habbal (1999) and shows total electron content and the corresponding polarized brightness (path-integrated electron density) observed at $1.15 R_\odot$ by the Mauna Loa Mk III K-coronameter. Panel *c* shows Doppler measurements at a sampling rate of 1 per 10 s, while panel *d* shows the rms of the Doppler measurements every 3 minutes along with the ranging results of panel *b*.

Filamentary structures may be attributed directly to the intermittency of the magnetic fields at the solar surface (e.g., Golub & Pasachoff 1997, p. 200). In the outer corona above the closed structures, Doppler measures the steep transverse gradients of the filamentary structures that trace the open mag-

netic field lines as they corotate with the Sun across the radio path. The variation of these gradients is shown in the Doppler time series of Figure 1c, which has a sampling rate of one per 10 s, corresponding to a scale size of 20 km or $0''.03$ at the Sun. That the transverse gradients vary significantly implies that the line-of-sight filling factor of the filamentary structures must not be high.

Note that polar plumes (Newkirk & Harvey 1968; DeForest et al. 1997) are also detected in the ranging measurements of the polar coronal hole in Figure 1b, as discussed by Woo & Habbal (1997a), and thus coexist with the finer structures. With a period of around a day (Woo 1996c; Woo & Habbal 1997a), they are a factor of 10^3 larger than the finer structures investigated here.

At the Sun, filamentary structures in active regions might be expected to have the steepest transverse gradients because of the enhanced complexity (includes neutral line) and strength of the magnetic fields there, while those in the polar coronal hole might be expected to have the shallowest gradients. Indeed, the largest peak-to-peak Doppler variations corresponding to the steepest gradients in Figure 1c are found in the outer corona overlying an active region (day of year [DOY] 68), and the shallowest gradients are found overlying the polar coronal hole (DOY 58). This implies that the ultra-fine-scale filamentary structures must extend radially from the Sun and that the magnetic field that traces them must be predominantly radial.

The transverse gradients of the ultra-fine-scale filamentary structures can be quantitatively characterized by the rms of the Doppler variations, which has been computed every 3 minutes and is displayed in Figure 1d along with the total electron content from Figure 1a. The logarithmic vertical scales for both ranging and Doppler measurements have been made similar to allow for the comparison of relative changes. The rms Doppler fluctuations show a uniform factor of 2–3 “fuzz” superposed on the much larger and systematic variation. Simulation studies affirm that this represents the estimation noise due to the finite sample size (e.g., Jenkins & Watts 1968). The correlation between the “average” of the rms Doppler fluctuations and ranging in Figure 1d is striking. Since the ranging measurements also reflect the density at the base of the corona as shown in Figure 1b, this correlation reinforces the fact that the transverse gradients of the filamentary structures are organized by the density at their source region on the Sun and that the filamentary structures are predominantly radial throughout the corona. Thus, while the ranging and pB measurements in Figure 1b imply a predominantly radial coronal field, simultaneous Doppler measurements of individual ultra-fine-scale filamentary structures tracing the magnetic field confirm it.

A break in the power spectrum of the Doppler time series, separating the lower frequency steeper power-law portion dominated by filamentary structures from the higher frequency shallower power-law portion dominated by convected turbulence, defines the finest observed scale of the filamentary structures (Woo & Habbal 1997b). Spectra of the time series in Figure 1c (displayed in Figs. 6–7 of Pätzold et al. 1996) show that the break frequency of the polar coronal hole spectrum is 0.06 Hz, corresponding to the finest scale of ~ 31 km at the Sun, while that of the active region labeled coronal streamer is 0.2–0.35 Hz, corresponding to the finest scale of ~ 5 –9 km at the Sun. That the finest filamentary structures emanate from the active region (factor of 3–6 smaller than in the polar coronal hole) is consistent with expectations based on heat transport and photospheric flux bundle packing considerations (Golub & Pasachoff 1997, p. 202). The finest scales observed closer to the Sun (Woo & Habbal 1997b; Imamura et al.

2005) are smaller, having higher frequency break points than those observed here, indicating that the smallest scale evolves with radial distance.

Since the levels of the power spectrum of the Doppler fluctuations covering both filamentary structures (steeper power law) and convected turbulence (shallower power law) rise and fall together (Pätzold et al. 1996; Woo & Habbal 1997b), turbulence inhomogeneities associated with active regions also have the steepest gradients, which explains why enhanced intensity scintillation is correlated with active regions (Hick et al. 1995). The steepest density gradients of filamentary structures and convected turbulence are a consequence of the strength and complexity of the magnetic field in active regions. That the high-altitude density fluctuations are proportional to density at the Sun and expand radially explains why density fluctuations observed by radio propagation and scattering measurements have always seemed to serve as a proxy for density (see, e.g., Erickson 1964; Newkirk 1967; Woo 1996b).

3. RELATIONSHIP TO PHOTOSPHERIC FIELDS

Since ubiquitous open magnetic field lines comprise the radially extended solar wind and are rooted in the entire Sun, their characteristics must be closely related to those of the intermittent small-scale photospheric field. This is borne out in the spectral description of the small-scale density structures, which is especially well determined by high-resolution and high-precision Doppler or integrated Doppler (phase) measurements (see, e.g., Woo & Armstrong 1979). Since the one-dimensional power-law density spectrum has a spectral index that is one less than that of the phase spectrum (Ishimaru 1978, p. 526), the phase spectra (see Fig. 7 in Pätzold et al. 1996) indicate that the density spectrum of the filamentary structures follows $\sim f^{-1.7}$ for the active region and $\sim f^{-1.3}$ for the high-latitude quiet Sun. These results are strikingly similar to the power spectra of the longitudinal magnetic field in the photosphere that are described by $\sim k^{-1.7}$ in the active region and by $\sim k^{-1.3}$ in the quiet region, where k is the spatial wavenumber (Abramenko et al. 2001). Related to the fluctuating frequency by the rotation rate of the Sun, the k -range of the magnetic spectra of $0.77\text{--}4.57\text{ Mm}^{-1}$ translates to the frequency range of $2.3 \times 10^{-4}\text{--}1.4 \times 10^{-3}\text{ Hz}$, which corresponds to the lowest frequency portion of the phase spectra.

The relating of magnetic and density spectra suggests that the magnetic field spectra extend to scales as small as a few kilometers. That the density spectrum lacks discontinuities or breaks corresponding to the granular structure in the magnetic field pattern (see Abramenko et al. 2001 and references therein) is consistent with the presence of significant internetwork fields (Lin & Rimmele 1999; Domínguez Cerdeña et al. 2003) and the anchoring of the coronal magnetic field in the internetwork rather than the network field (Schrijver & Title 2003).

The association between magnetic and density spectra also clarifies the picture of the density spectra in the solar corona. Since the density spectrum level is higher in active regions than in quiet regions, the steeper Kolmogorov spectrum dominates all path-integrated measurements of the phase spectra at low latitude (Woo & Armstrong 1979; Coles et al. 1991; Imamura et al. 2005). Only at high latitude, where quiet regions are isolated from active regions, is the shallower spectrum of the quiet photospheric magnetic fields revealed (Woo & Armstrong 1979; Pätzold et al. 1996). On the other hand, because the break in the spectrum occurs at a higher frequency in active regions than in quiet regions, measurements of break frequency are able to

pinpoint active regions at low latitude better than those of the spectrum shape (see Fig. 7 of Pätzold et al. 1996).

Intermittent photospheric magnetic fields emerge onto the solar surface as bipolar regions with a broad range of length scales. On large scales, the bipolar regions are produced by the (large-scale) solar dynamo and persist for a month or longer before dispersing diffusively (Leighton 1964; Wang et al. 1989). On the smaller scales, individual bipolar regions disappear within days but are continuously replenished by new small flux concentrations, implying continuous reconnection (Schrijver et al. 1997, 1998). On even smaller scales, magnetic fields pop up, evolve, and fade with spatial and temporal scales characteristic of the solar granulation (e.g., Lin & Rimmele 1999; Domínguez Cerdeña et al. 2003). A turbulent dynamo, driven by the granular and supergranular flows (Cattaneo 1999) or the whole convection zone (Stein & Nordlund 2002), may generate all these small-scale magnetic structures. Abramenko et al. (2001) have suggested that the shallower spectral index of the magnetic power spectrum in the quiet-Sun photosphere is due to small-scale dynamo action, and they have used the spectrum to estimate the magnetic energy generated by it.

Coronal results, on the other hand, have shown that closed fields at the base of the corona confine plasma for long durations and that this trapped plasma must be released by continual small-scale reconnection in order for it to carry the imprint of the Sun into interplanetary space (Woo et al. 2004). The filamentary structures observed in this Letter, therefore, provide direct evidence of the open magnetic field lines that couple the photosphere and the base of the corona to the solar wind through the process of small-scale reconnection (e.g., Ryutova et al. 2003; Isobe et al. 2005). That the ultra-fine-scale structures are likely associated with hidden magnetic energy (Trujillo Bueno et al. 2004) and possibly strong fields (Domínguez Cerdeña et al. 2003) indicates that small-scale structure must play an important role in coronal heating and solar wind acceleration. It is interesting that, if this were the case, there is an impression from the observations that the dynamics of the small-scale bipolar regions is providing energy to overcome the presence and influence (trapping ability) of the larger scale bipolar regions in order to accelerate the solar wind. In this regard, it is significant that the solar wind is rooted in the entire Sun and hence, to a large extent, the quiet Sun, because recent studies (Sánchez Almeida 2003) suggest that virtually all of the photospheric magnetic energy and unsigned flux are in the quiet Sun rather than in active regions. These results, therefore, elucidate the dual nature of the coronal magnetic field (Aschwanden et al. 2001).

With the lack of coronal magnetic field measurements, theoretical models have been employed to extrapolate observed photospheric fields into the corona, and these models now dominate solar wind studies (e.g., Neugebauer et al. 1998; Linker et al. 1999). Not accounting for filamentary structures and their dynamics is one reason why these widespread models incorrectly predict the source of the solar wind, limiting it to coronal holes instead of the entire Sun. Alternative models that include the process of reconnection and open field lines are more observationally relevant and promising (Fisk & Schwadron 2001; Fisk 2005).

4. CONCLUSIONS

We have used Doppler measurements to investigate the transverse gradients of the ultra-fine-scale structures that pervade the outer corona. The two new results are that the filamentary

structures are predominantly radial and that they are rooted in the entire Sun. The former provides direct evidence of the predominantly radial coronal magnetic field that is apparently responsible for the radial expansion of the solar wind and reaffirms that the absence of these hidden structures from current coronal imaging leads to incorrect conclusions about the influence of the coronal magnetic field on solar wind flow (Woo 2005). The latter provides key insight into the solar magnetic field and its coupling between the solar wind and the photosphere. First, it changes the widely held belief that open field lines in the inner corona are exclusive to coronal holes, reinforcing that emission measurements of the Sun, such as those of soft X-rays and EUV, give a false impression of the absence of open field lines because of the dominance of enhanced emission by closed structures. Second, that filamentary structures extend to the outer corona means that they carry with them information about the magnetic field at the Sun, as reassured by the similarity in power spectra of the photospheric magnetic field and coronal density fluctuations. Thus, the Doppler measurements show that filamentary structures in the vicinity of active regions have the steepest transverse gradient and finest scale, while those in polar coronal holes have the shallowest

transverse gradients and least finest scale. Third, when the anchoring of filamentary structures in the entire photosphere is combined with the existence of hidden magnetic energy in the quiet Sun, it is clear that small-scale and/or subresolution magnetic fields must play a crucial role not only in the magnetic coupling between the photosphere and corona, but also in coronal heating and wind acceleration through the process of small-scale magnetic reconnection. Finally, the presence of open field lines throughout the inner corona explains why current theoretical models that exclude them are in conflict with observations in predicting the source of the solar wind.

It is a pleasure to thank J. W. Armstrong for performing the simulation studies of the estimation noise and V. Abramenko, J. W. Armstrong, S. R. Habbal, E. N. Parker, M. Ryutova, J. Sánchez Almeida, and T. D. Tarbell for stimulating and useful discussions. This research was carried out at the Jet Propulsion Laboratory (JPL), California Institute of Technology, under a contract with the National Aeronautics and Space Administration. I would also like to acknowledge the JPL sabbatical program without which the work reported here would not have been possible.

REFERENCES

- Abramenko, V., Yurchyshyn, V., Wang, H., & Goode, P. R. 2001, *Sol. Phys.*, 201, 225
- Alfvén, H. 1963, in *IAU Symp. 16, The Solar Corona*, ed. J. W. Evans (New York: Academic), 35
- Arnaud, J., & Newkirk, G., Jr. 1987, *A&A*, 178, 263
- Aschwanden, M. J. 2004, *Physics of the Solar Corona* (Chichester: Springer-Praxis)
- Aschwanden, M. J., Poland, A. I., & Rabin, D. M. 2001, *ARA&A*, 39, 175
- Bird, M. K., & Edenhofer, P. 1990, in *Physics of the Inner Heliosphere I*, ed. R. Schwenn & E. Marsch (Berlin: Springer), 13
- Cattaneo, F. 1999, *ApJ*, 515, L39
- Coles, W. A., Liu, W., Harmon, J. K., & Martin, C. L. 1991, *J. Geophys. Res.*, 96, 1745
- DeForest, C. E., Hoeksema, J. T., Gurman, J. B., Thompson, B. J., Plunkett, S. P., Howard, R., Harrison, R. C., & Hasslerz, D. M. 1997, *Sol. Phys.*, 175, 393
- Domínguez Cerdeña, I., Kneer, F., & Sánchez Almeida, J. 2003, *ApJ*, 582, L55
- Eddy, J. A., Lee, R. H., & Emerson, J. P. 1973, *Sol. Phys.*, 30, 385
- Ekers, R. D., & Little, L. T. 1971, *A&A*, 10, 310
- Erickson, W. C. 1964, *ApJ*, 139, 1290
- Fisk, L. A. 2005, *ApJ*, 626, 563
- Fisk, L. A., & Schwadron, N. A. 2001, *ApJ*, 560, 425
- Golub, L., & Pasachoff, J. M. 1997, *The Solar Corona* (Cambridge: Cambridge Univ. Press)
- Grall, R. R., Coles, W. A., Klinglesmith, M. T., Breen, A. R., Williams, P. J. S., Markkanen, J., & Esser, R. 1996, *Nature*, 379, 429
- Habbal, S. R., Woo, R., & Arnaud, J. 2001, *ApJ*, 558, 852
- Hewish, A. 1972, in *Solar Wind Three*, ed. C. P. Sonnett, P. J. Coleman, Jr., & J. M. Wilcox (SP-308; Washington, DC: NASA), 477
- Hick, P., et al. 1995, *Geophys. Res. Lett.*, 22, 643
- Hundhausen, A. D. 1977, in *Coronal Holes and High Speed Streams*, ed. J. B. Zirker (Boulder: Colorado Assoc. Univ. Press), 225
- Imamura, T., Noguchi, K., Nabatov, A., Oyama, K.-I., Yamamoto, Z., & Tokumaru, M. 2005, *A&A*, 439, 1165
- Ishimaru, A., 1978, *Wave Propagation and Scattering in Random Media*, Vol. 2 (New York: Academic)
- Isobe, H., Miyagoshi, T., Shibata, K., & Yokoyama, T. 2005, *Nature*, 434, 478
- Jenkins, G. M., & Watts, D. G. 1968, *Spectral Analysis and Its Applications* (San Francisco: Holden-Day)
- Leighton, R. B. 1964, *ApJ*, 140, 1547
- Lin, H., & Rimmele, T. 1999, *ApJ*, 514, 448
- Linker, J. A., et al. 1999, *J. Geophys. Res.*, 104, 9809
- Litwin, C., & Rosner, R. 1993, *ApJ*, 412, 375
- Lockyer, J. N. 1874, *Contributions to Solar Physics* (London: Macmillan)
- Menzel, D. H. 1959, *Our Sun* (Cambridge: Harvard Univ. Press)
- Munro, R. H., & Jackson, B. V. 1977, *ApJ*, 213, 874
- Neugebauer, M., et al. 1998, *J. Geophys. Res.*, 103, 14587
- Newkirk, G., Jr. 1967, *ARA&A*, 5, 213
- Newkirk, G., Jr., & Harvey, J. 1968, *Sol. Phys.*, 3, 321
- Parker, E. N. 1964, *ApJ*, 139, 690
- Pätzold, M., Karl, J., & Bird, M. K. 1996, *A&A*, 316, 449
- Ryutova, M., Tarbell, T. D., & Shine, R. 2003, *Sol. Phys.*, 213, 231
- Sánchez Almeida, J. 2003 in *AIP Conf. Proc. 679, Solar Wind Ten*, ed. M. Velli, R. Bruno, & F. Malara (Melville: AIP), 293
- Scharmer, G. B., Gudiksen, B. V., Kiselman, D., Löfdahl, M. G., & Rouppe van der Voort, L. H. M. 2002, *Nature*, 420, 151
- Schrijver, C. J., & Title, A. M. 2003, *ApJ*, 597, L165
- Schrijver, C. J., Title, A. M., van Ballegooijen, A. A., Hagenaar, H. J., & Shine, R. A. 1997, *ApJ*, 487, 424
- Schrijver, C. J., et al. 1998, *Nature*, 394, 152
- Stein, R. F., & Nordlund, Å. 2002, in *SOLMAG 2002: Magnetic Coupling of the Solar Atmosphere Euroconference and IAU Colloq. 188*, ed. H. Sawaya-Lacoste (ESA SP-505; Noordwijk: ESA), 83
- Trujillo Bueno, J., Shchukina, N., & Asensio Ramos, A. 2004, *Nature*, 430, 326
- Wang, Y.-M., Nash, A. G., & Sheeley, N. R., Jr. 1989, *Science*, 245, 712
- Woo, R. 1992, in *Wave Propagation in Random Media (Scintillation)*, ed. V. I. Tatarskii, A. Ishimaru, & V. U. Zavorotny (Bellingham: SPIE), 50
- . 1996a, *Nature*, 379, 321
- . 1996b, in *AIP Conf. Proc. 382, Solar Wind Eight*, ed. D. Winterhalter et al. (Woodbury: AIP), 38
- . 1996c, *ApJ*, 464, L95
- . 2005, *Sol. Phys.*, 231, 71
- Woo, R., & Armstrong, J. W. 1979, *J. Geophys. Res.*, 84, 7288
- Woo, R., Armstrong, J. W., & Habbal, S. R. 2000, *ApJ*, 538, L171
- Woo, R., & Habbal, S. R. 1997a, *Geophys. Res. Lett.*, 24, 1159
- . 1997b, *ApJ*, 474, L139
- . 1999, *ApJ*, 510, L69
- Woo, R., Habbal, S. R., & Feldman, U. 2004, *ApJ*, 612, 1171